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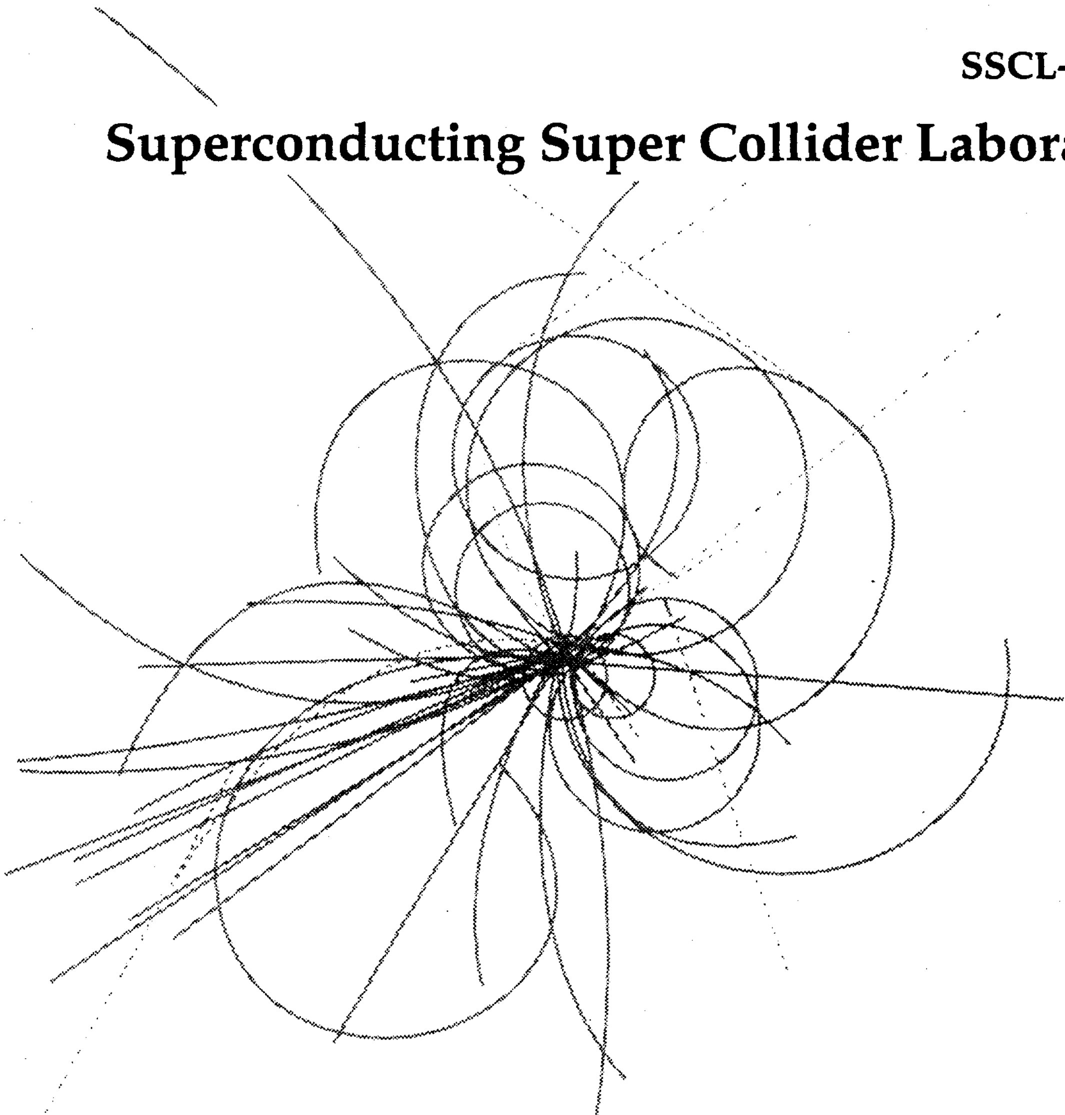

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OPTICAL TRANSDUCERS FOR SCINTILLATING FIBER READOUT

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ABSTRACT

Characteristics of optical-to-electronic transducers which are currently on the market or which will soon be available are discussed in the context of particle detectors using scintillating and wavelength-shifting fibers. It is shown that the most promising avenue for progress in detector development is via the use of solid state transducers, and that these would benefit from the development of long-wavelength light emitters.

KEYWORDS

Scintillating Fiber, APD, Avalanche Photodiode, VLPC, Photocathode, Quantum Efficiency, Tracker, Calorimeter, Shower Maximum

INTRODUCTION

Many reports in this conference have described endeavors to understand or improve the light production and transmission performance and stability of plastics and flours after they have been exposed to radiation, mechanical, thermal, and other stress. In this report I will summarize the work of myself and others which has been directed towards developing and choosing appropriate sensors for that light. Clearly, it is crucial that the development of scintillators and waveshifters proceed with an understanding of the characteristics of the transducers which must convert the optical signal into an electronic one. It is appropriate to review the status of optical transducers at this particular point in time because recent advances in solid state detectors may dramatically alter the acceptable spectrum of light produced by scintillators and waveshifters.

OPTICAL DETECTOR REQUIREMENTS

At the SSC and other laboratories there are currently plans to employ both scintillating fibers and wavelength shifting fibers in various sections of the major detectors (Trilling et al. 1991). For calorimetry, both scintillating tiles with wavelength shifter readout and "spaghetti" style detectors are envisioned. In each of these cases several fibers would be terminated at the face of a single transducer in order to collect the light from an entire tower of the calorimeter. Such arrangements minimize the number of electronics channels required, but simultaneously specify a minimum transducer area and may require complicated filters to balance the response from different depths in the calorimeter. Given the large area required of the transducers and the number of channels involved, conventional photomultiplier tubes, perhaps with an improved photocathode, are a

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natural choice for such detectors. (Note, however, that even the most promising of the new generation of photocathodes have peak quantum efficiencies of only about 30%.) It is still worthwhile for those building these detectors to keep watch on the developments in the solid state detector arena, however.

A preshower or shower-maximum detector, on the other hand, measures the light from each of a large number of channels independently in order to provide tracking and particle identification possibilities. Here the need is for a large number of small area transducers that provide outputs which reflect the magnitude of the input signal. Continuing towards the limit of fine segmentation we come to scintillating fiber tracking detectors. These may involve a huge number of independent channels in order to achieve the desired coverage and resolution (B. Abbot, et al., 1992). They are fundamentally binary channels, however, reporting simply "hit" or "not hit". There are even discussions of building muon detectors out of bars of scintillators with waveshifting fibers embedded along their length. Their optical signals would be detected similarly to those from tracking fibers.

Concentrating on the detectors with very large numbers of physically small channels we can summarize the requirements as follows.

Optical Detector Requirements

Shower Maximum Detector Application
- Linear dynamic range of 4000.
- Sensitive to a minimum of 10 photons.
- Crosstalk between channels < 1%.
- Channel-to-channel variations < 3:1.
- Bandwidth sufficient to enable event separation.
- Radiation-hard for ten years of operation in the planned environment.

Tracking Detector Application
- Efficiency for detecting signals from the associated fiber > 95% (e.g. >50% detected quantum efficiency for a fiber which emits an average of 6 photons).
- Noise rate < 10% of the occupancy probability in the planned application.
- Pulse resolution sufficient to enable event separation.
- Radiation hardness as above.

Obvious common additions to this list include high channel density, low power consumption, and low cost.

TRANSDUCER CHARACTERISTICS

Table 1 summarizes the characteristics of optical detectors which are currently available. While image intensifiers combined with charge-coupled device readouts provide high channel counts at affordable prices, they are intrinsicly slow and, even with very clever triggering schemes, are limited to event rates less than a few MHz. Photomultipliers represent a well understood technology, but are inappropriate when high density is demanded. Position sensitive photomultipliers and channel-plate photomultipliers allow high channel densities, but suffer from significant crosstalk (optical and/or electrical), and channel-plates have the additional disadvantage of being limited in rate by the maximum tolerable strip current. Conventional photodiodes are an attractive alternative when the amount of light to be measured is quite large (thousands of photons), which is not the case for most fiber applications.

The only truly promising alternatives for use with individual channels of scintillating/optical fiber detectors are solid state photomultipliers (SSPMs -- the VLPC, or "visible light photon counter", is the non-restricted version of this device) and avalanche photodiodes (APDs). These offer high-density, high-gain, and high-efficiency performance.

Table 1. Summary Comparison of Optical Detectors (after Kuroda, et al. 1991)

Type	Remarks
Optoelectronic device (II + CCD)	Good spatial resolution, successful applications. // Low performance in time characteristics (decay time of phosphors 50-100 ns, readout time of CCD ≈ 1ms).
Photomultiplier	Fast, simple and reliable. // Low granularity, bulky setup.
Photodiode	Simple, compact. // Low sensitivity.
Solid State Photomultiplier (VLPC)	Excellent sensitivity, good energy resolution. // Operation at 7K, few data on long-term stability, radiation hardness.
Position Sensitive Photomultiplier	Intrinsic merits of PM + compactness, insensitivity to magnetic field. // Crosstalk, nonuniformity of gain.
Channel-Plate Photomultiplier	High resolution in space and time. // Saturation in count rate, crosstalk.
Avalanche Photodiode	Compact, high QE, many suppliers. Very large gain in Geiger mode. // Requires stable temperature and bias. Linear mode: gain variations; Geiger mode: deadtime after pulse.

VISIBLE LIGHT PHOTON COUNTERS

VLPCs are the result of combining band-gap engineering (to achieve avalanche multiplication in silicon with low electric fields) and field-shaping (to provide the necessary fields for charge collection and amplification). In order to eliminate spurious signals caused by thermal electrons in the silicon lattice, VLPCs must be operated at temperatures around 7K -- usually achieved with a liquid helium heat sink. They exhibit excellent photon counting characteristics, allowing one to distinguish among pulses initiated by as many as ten photoelectrons (M. Atac, et al., 1991) as shown in Fig. 1. Their detected quantum efficiencies have ranged as high as 80% in some production runs, and they provide gains approaching 10^4. They have a dynamic range of only about 1000, however, making them unattractive for most calorimetry applications. Owing to their high quantum efficiency and low noise rate, they appear to be excellent transducers for scintillating fiber tracking applications. To date there is only one supplier of these devices and the distribution of SSPMs has been hampered by U.S. military secrecy restrictions. The VLPC is a recently developed non-restricted version of the SSPM, and orders for them are being processed and delivered. They are being fabricated in linear arrays of up to 12 elements. There is no broad body of experience with using them as of this writing, however.

AVALANCHE PHOTODIODES

Avalanche photodiodes have been around for decades. They, too, employ avalanche multiplication in a silicon structure, but they operate at room temperature and higher electric field intensities than the band-gap engineered VLPCs. They exhibit gain in two distinct modes. In the "linear" mode APDs provide an electrical output which ranges from about 10^2 to about 10^3 electrons output per input photo-electron. Thus the output is proportional to the input, over a dynamic range as high as 10^5, and they can find applications in calorimetry. The SDC experiment at SSC has, in fact, chosen APDs as the transducers for their shower-maximum detector. Figure 2 shows the different signals observed in a beam test of a prototype SDC shower maximum detector exposed to 35 GeV/c pions and electrons and read out with avalanche photodiodes.

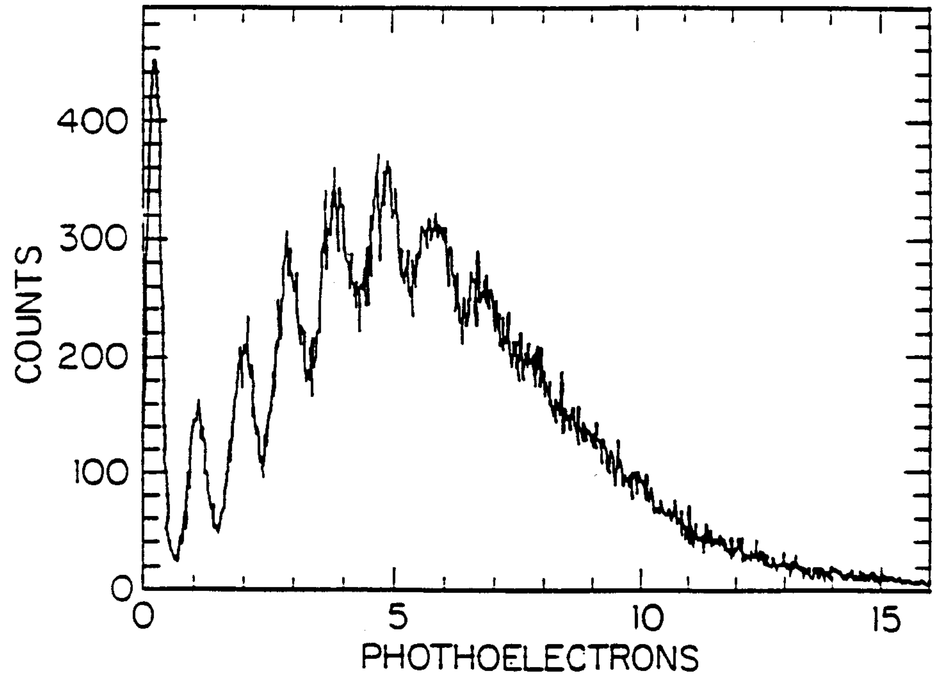

Fig. 1. Pulse height spectrum obtained from a Visible Light Photon Counter used to detect the light from a scintillating fiber during a cosmic ray test.

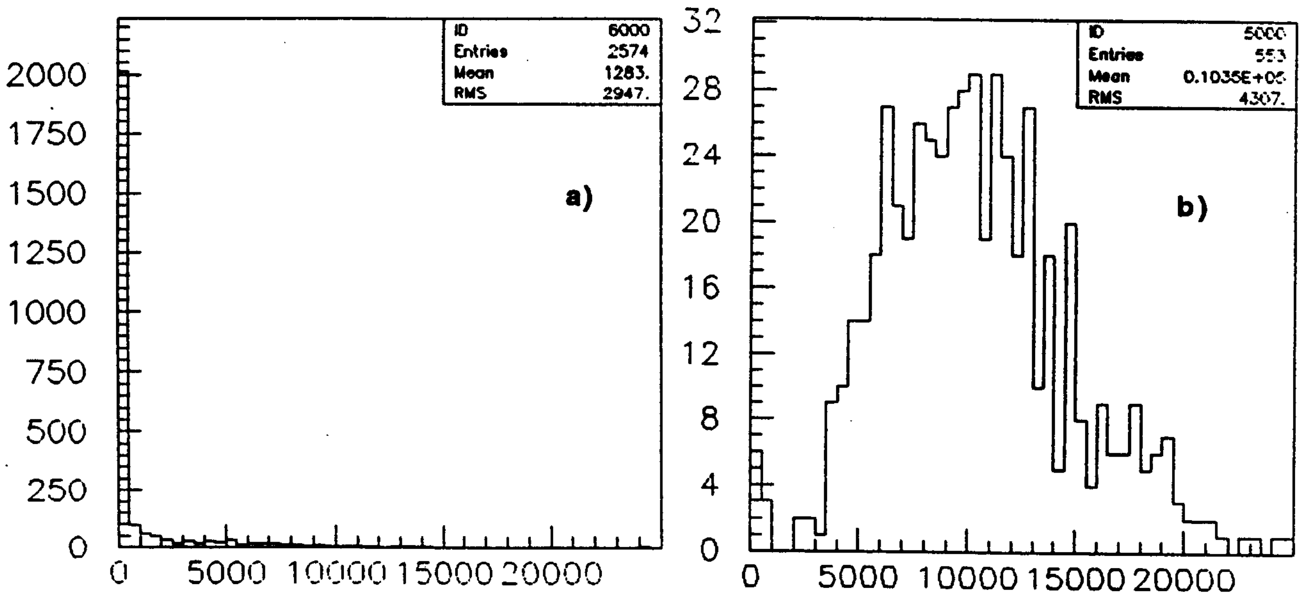

Fig. 2. Response of a Shower Maximum Detector with Avalanche Photodiode Readout. The detector was exposed to 35 GeV/c pions (a) and electrons (b). This result demonstrates that APDs used in this type of calorimetry allow one to distinguish these two species of particles.

APDs are not single photon counters, however, as they exhibit large gain dispersion which prevents the counting of small numbers of photons. The detected quantum efficiency in APDs ranges up to about 80% at the peak of spectral sensitivity (usually around 800 nm).

If one raises the bias voltage across an APD above the breakdown voltage the APD begins to operate in Geiger mode, analogous to the Geiger operation of a wire chamber. In this way huge gains (~10^8) may be achieved, and single photons are capable of producing a signal directly detectable by logic gates (not recommended)! The electrical pulse output is not proportional to the light signal applied in this case, but for tracking this is of no consequence. What is of consequence for tracking is the fact that APDs simply biased through a high resistance and operated in Geiger mode typically have a recovery time after each pulse which is of order one microsecond. *This is clearly unacceptable for SSC detectors, and is unacceptable for most other* detector applications as well.

Recent developments (T. Regan, et al., 1992) in the Detector Physics Laboratory at SSC provide hope that APDs may be used in high rate situations. There we have developed a novel circuit which detects the onset of an APD Geiger avalanche and quickly starves the APD of bias current. Simultaneously a logic pulse is provided to the outside world to signal that the APD fired. After a fixed time which is determined empirically the circuit recharges the APD through a low impedance then resets itself to await another avalanche. Using a 0.5 mm diameter RCA 30902S APD with this circuit, we are able to observe a train of light pulses separated by less than 50 ns. Figure 3 shows an oscilloscope trace demonstrating this achievement. An eight-channel VLSI version of this circuit has been designed at the SSC and prototype chips are being fabricated. It is expected that these chips will provide even more rapid quench/recharge capabilities. Systematic studies of the behavior of this system as a photon detector are being conducted now at SSC.

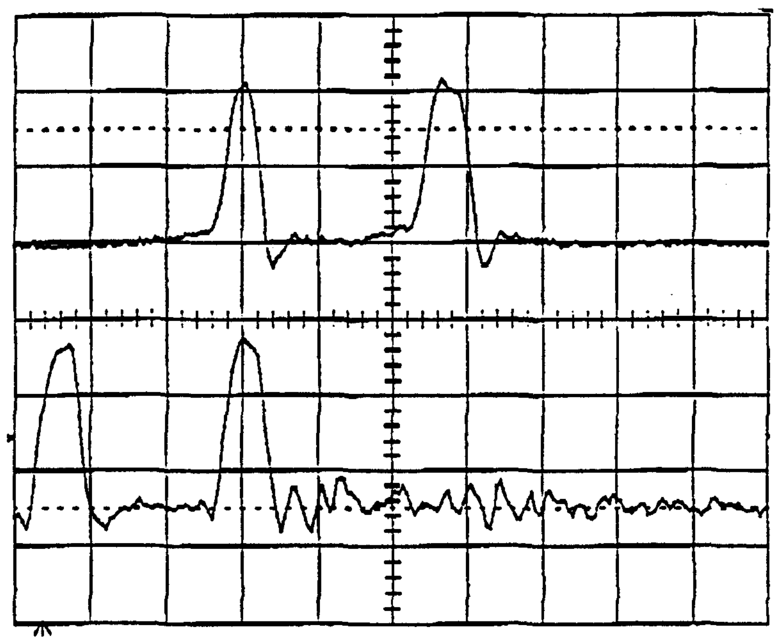

Fig. 3 Oscilloscope trace showing the response of an Avalanche Photodiode and fast quench/recharge circuit (top trace) to a pair of light pulses separated by 50ns. The bottom trace is the voltage waveform of a laser diode which produced the light. The horizontal scale is 20 ns/div. The vertical scales are 2 V/div. (top), and 200 mV/div. (bottom).

Avalanche photodiodes may be purchased in a number of sizes ranging from about 0.5 mm up to 2 cm in diameter. There is work going on to produce two-dimensional arrays of APD pixels, prototypes of which are undergoing tests now.

SUMMARY

Figure 4 shows the spectral responsivity of a typical bialkali photocathode, a VLPC, and an APD. Indicated as vertical lines are the points of peak emission of all of the scintillating plastic listed in a recent edition of the Bicron Corporation catalog (Bicron, 1991). Clearly there is a nice overlap between the photocathode and the majority of the emission lines -- ultraviolet to blue-green. Note, however, that the solid state detectors have peak sensitivities at longer wavelengths. As these are the transducers which are being seriously considered for fiber tracking and calorimetry applications, and as these are the transducers which have high quantum efficiencies and can be built in high density arrangements as required for future particle detectors, it is clear that the HEP research community would benefit from the existence of a scintillator and/or wavelength shifter with high output in the red end of the spectrum.

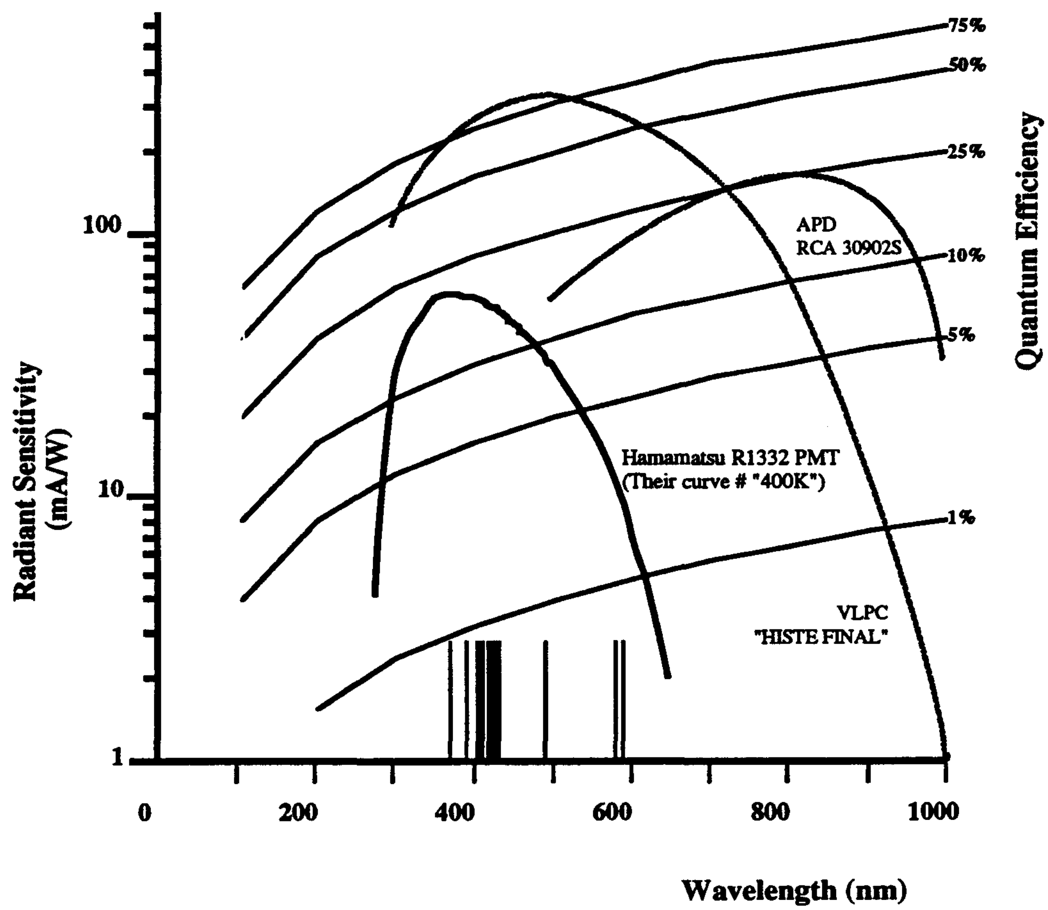

Fig. 4. Comparison of spectral sensitivity of APDs, VLPCs, a typical Bialkali Photocathode, and a representative sample of the peak emission lines of available plastic scintillators.

Working tracking detectors have been built using both VLPCs and APDs (W. Bruckner, et al., 1991) and more ambitious prototypes are going into test beams this summer. Data was shown in this report demonstrating that APDs are a viable choice for shower-maximum calorimeter compartments. It seems almost certain that one or both of these devices will see widespread use in particle detectors in the near future. It is perhaps a great benefit that they exhibit their greatest sensitivity in that portion of the light spectrum which appears to be least affected by radiation damage, as shown by many talks presented at this conference.

REFERENCES

Abbot, B. et al., 1992. Conceptual Design: Scintillating Fiber Outer Tracking. SDC-92-174. SSC Publication.

Atac, M. et al., 1991. Scintillating Fiber Tracking for the SSC Using Visible Light Photon Counters, UCLA-PPH0034-7/91

Bicron, 1991. Bicron Corporation, 12345 Kinsman Road, Newbury, Ohio 44065, U.S.A.

Bruckner, W. et al., 1991. A Scintillating Fiber Hodoscope with Avalanche Photodiode Readout. CERN-PPe-91-146 (Submitted to *Nucl. Inst. and Meth.*)

Kuroda, K. et al., 1991. Ultrafast Readout of Scintillating Fibers Using Upgraded Position-Sensitive Photomultipliers. Test proposal to CERN LHC.

Regan, T. et al., 1992. A Method to Quench and Recharge Avalanche Photodiodes for use in High Rate Situations. (Submitted to *Nucl. Inst. and Meth.*)

Trilling, G. et al., 1991. SDC Technical Design Report, SSC Laboratory Publication.